

Contents

Preface	xiii
Symbols and Abbreviations	xv
1. Cells and Diffusion	3
1.1. Cell Structure	3
1.1A. Generalized Plant Cell	3
1.1B. Leaf Anatomy	5
1.1C. Vascular Tissue	7
1.1D. Root Anatomy	9
1.2. Diffusion	11
1.2A. Fick's First Law	12
1.2B. Continuity Equation and Fick's Second Law	13
1.2C. Time-Distance Relation for Diffusion	16
1.3. Membrane Structure	20
1.3A. Membrane Models	21
1.3B. Organelle Membranes	22
1.4. Membrane Permeability	25
1.4A. Concentration Difference Across a Membrane	26
1.4B. Permeability Coefficient	28
1.4C. Diffusion and Cellular Concentration	29
1.5. Cell Walls	31
1.5A. Chemistry and Morphology	32
1.5B. Diffusion Across Cell Walls	33
1.5C. Stress-Strain Relations of Cell Walls	36
1.6. Problems	40
1.7. References	42
2. Water	45
2.1. Physical Properties	46
2.1A. Hydrogen Bonding—Thermal Relations	47
2.1B. Surface Tension	49
2.1C. Capillary Rise	50
2.1D. Capillary Rise in the Xylem	52

2.1E.	Tensile Strength, Viscosity	53
2.1F.	Electrical Properties	54
2.2.	Chemical Potential	56
2.2A.	Free Energy and Chemical Potential	56
2.2B.	Analysis of Chemical Potential	59
2.2C.	Standard State	62
2.2D.	Hydrostatic Pressure	63
2.2E.	Water Activity and Osmotic Pressure	64
2.2F.	Van't Hoff Relation	65
2.2G.	Matric Pressure	68
2.2H.	Water Potential	69
2.3.	Central Vacuole and Chloroplasts	70
2.3A.	Water Relations of the Central Vacuole	71
2.3B.	Boyle–Van't Hoff Relation	73
2.3C.	Osmotic Responses of Chloroplasts	74
2.4.	Water Potential and Plant Cells	77
2.4A.	Incipient Plasmolysis	77
2.4B.	Höfler Diagram and Pressure–Volume Curve	79
2.4C.	Chemical Potential and Water Potential of Water Vapor	82
2.4D.	Plant–Air Interface	86
2.4E.	Pressure in the Cell Wall Water	87
2.4F.	Water Flux	89
2.4G.	Cell Growth	91
2.4H.	Kinetics of Volume Changes	93
2.5.	Problems	94
2.6.	References	96

3. Solutes 99

3.1.	Chemical Potential of Ions	100
3.1A.	Electrical Potential	101
3.1B.	Electroneutrality and Membrane Capacitance	102
3.1C.	Activity Coefficients of Ions	104
3.1D.	Nernst Potential	106
3.1E.	Example of E_{N_K}	108
3.2.	Fluxes and Diffusion Potentials	109
3.2A.	Flux and Mobility	110
3.2B.	Diffusion Potential in a Solution	113
3.2C.	Membrane Fluxes	116
3.2D.	Membrane Diffusion Potential — Goldman Equation	119
3.2E.	Application of Goldman Equation	123
3.2F.	Donnan Potential	124
3.3.	Characteristics of Crossing Membranes	126
3.3A.	Electrogenicity	127
3.3B.	Boltzmann Energy Distribution and Q_{10} , a Temperature Coefficient	128
3.3C.	Activation Energy and Arrhenius Plots	131
3.3D.	Ussing–Teorell Equation	134

3.3E. Example of Active Transport	136
3.3F. Energy for Active Transport	139
3.3G. Speculation on Active Transport	140
3.4. Mechanisms for Crossing Membranes	141
3.4A. Carriers, Porters, Channels, and Pumps	141
3.4B. Michaelis–Menten Formalism	145
3.4C. Facilitated Diffusion	147
3.5. Principles of Irreversible Thermodynamics	149
3.5A. Fluxes, Forces, and Onsager Coefficients	150
3.5B. Water and Solute Flow	151
3.5C. Flux Densities, L_P , and σ	153
3.5D. Values of Reflection Coefficients	156
3.6. Solute Movement Across Membranes	158
3.6A. Influence of Reflection Coefficients on Incipient Plasmolysis	160
3.6B. Extension of the Boyle–Van’t Hoff Relation	162
3.6C. Reflection Coefficients of Chloroplasts	164
3.6D. Solute Flux Density	164
3.7. Problems	165
3.8. References	168
4. Light	171
4.1. Wavelength and Energy	173
4.1A. Light Waves	173
4.1B. Energy of Light	175
4.1C. Illumination, Photon Flux Density, and Irradiance	177
4.1D. Sunlight	180
4.1E. Planck’s and Wien’s Formulae	182
4.2. Absorption of Light by Molecules	183
4.2A. Role of Electrons in Absorption Event	184
4.2B. Electron Spin and State Multiplicity	185
4.2C. Molecular Orbitals	187
4.2D. Photoisomerization	189
4.2E. Light Absorption by Chlorophyll	190
4.3. Deexcitation	192
4.3A. Fluorescence, Radiationless Transition, and Phosphorescence	193
4.3B. Competing Pathways for Deexcitation	194
4.3C. Lifetimes	197
4.3D. Quantum Yields	198
4.4. Absorption Spectra and Action Spectra	199
4.4A. Vibrational Sublevels	200
4.4B. The Franck–Condon Principle	202
4.4C. Absorption Bands and Absorption Coefficients	204
4.4D. Application of Beer’s Law	207
4.4E. Conjugation	208
4.4F. Action Spectra	209
4.4G. Absorption and Action Spectra of Phytochrome	210

4.5. Problems	214
4.6. References	216
5. Photochemistry of Photosynthesis	219
5.1. Chlorophyll—Chemistry and Spectra	222
5.1A. Types and Structures	222
5.1B. Absorption and Fluorescence Emission Spectra	223
5.1C. Absorption in Vivo—Polarized Light	226
5.2. Other Photosynthetic Pigments	228
5.2A. Carotenoids	228
5.2B. Phycobilins	232
5.2C. General Comments	234
5.3. Excitation Transfers Among Photosynthetic Pigments	235
5.3A. Pigments and the Photochemical Reaction	235
5.3B. Resonance Transfer of Excitation	237
5.3C. Specific Transfers of Excitation	239
5.3D. Excitation Trapping	240
5.4. Groupings of Photosynthetic Pigments	242
5.4A. Photon Processing	243
5.4B. Excitation Processing	243
5.4C. Photosynthetic Action Spectra and Enhancement Effects	245
5.4D. Two Photosystems Plus Light-Harvesting Antennae	246
5.5. Electron Flow	249
5.5A. Electron Flow Model	249
5.5B. Components of the Electron Transfer Pathway	251
5.5C. Types of Electron Flow	257
5.5D. Assessing Photochemistry Using Fluorescence	258
5.5E. Photophosphorylation	260
5.5F. Vectorial Aspects of Electron Flow	260
5.6. Problems	262
5.7. References	263
6. Bioenergetics	267
6.1. Gibbs Free Energy	268
6.1A. Chemical Reactions and Equilibrium Constants	269
6.1B. Interconversion of Chemical and Electrical Energy	272
6.1C. Redox Potentials	274
6.2. Biological Energy Currencies	276
6.2A. ATP—Structure and Reactions	277
6.2B. Gibbs Free Energy Change for ATP Formation	281
6.2C. NADP ⁺ -NADPH Redox Couple	283
6.3. Chloroplast Bioenergetics	284
6.3A. Redox Couples	285
6.3B. H ⁺ Chemical Potential Differences Caused by Electron Flow	288
6.3C. Evidence for Chemiosmotic Hypothesis	289
6.3D. Coupling of Flows	290

6.4.	Mitochondrial Bioenergetics	292
6.4A.	Electron Flow Components—Redox Potentials	293
6.4B.	Oxidative Phosphorylation	295
6.5.	Energy Flow in the Biosphere	298
6.5A.	Incident Light—Stefan–Boltzmann Law	299
6.5B.	Absorbed Light and Photosynthetic Efficiency	301
6.5C.	Food Chains and Material Cycles	302
6.6.	Problems	303
6.7.	References	305
7. Temperature and Energy Budgets		307
7.1.	Energy Budget—Radiation	308
7.1A.	Solar Irradiation	310
7.1B.	Absorbed Infrared Irradiation	314
7.1C.	Emitted Infrared Radiation	315
7.1D.	Values for a , a_{IR} , and e_{IR}	316
7.1E.	Net Radiation	318
7.1F.	Examples for Radiation Terms	318
7.2.	Wind—Heat Conduction and Convection	321
7.2A.	Wind	322
7.2B.	Air Boundary Layers	324
7.2C.	Boundary Layers for Bluff Bodies	326
7.2D.	Heat Conduction/Convection Equations	327
7.2E.	Dimensionless Numbers	329
7.2F.	Examples of Heat Conduction/Convection	332
7.3.	Latent Heat—Transpiration	333
7.3A.	Heat Flux Density Accompanying Transpiration	333
7.3B.	Heat Flux Density for Dew or Frost Formation	334
7.3C.	Examples of Frost and Dew Formation	335
7.4.	Further Examples of Energy Budgets	337
7.4A.	Leaf Shape and Orientation	337
7.4B.	Shaded Leaves within Plant Communities	339
7.4C.	Heat Storage	340
7.4D.	Time Constants	342
7.5.	Soil	343
7.5A.	Thermal Properties	343
7.5B.	Soil Energy Balance	344
7.5C.	Variations in Soil Temperature	345
7.6.	Problems	347
7.7.	References	349
8. Leaves and Fluxes		351
8.1.	Resistances and Conductances—Transpiration	352
8.1A.	Boundary Layer Adjacent to Leaf	354
8.1B.	Stomata	357
8.1C.	Stomatal Conductance and Resistance	359

8.1D. Cuticle	361
8.1E. Intercellular Air Spaces	362
8.1F. Fick's First Law and Conductances	363
8.2. Water Vapor Fluxes Accompanying Transpiration	366
8.2A. Conductance and Resistance Network	366
8.2B. Values of Conductances	369
8.2C. Effective Lengths and Resistance	370
8.2D. Water Vapor Concentrations and Mole Fractions for Leaves	371
8.2E. Examples of Water Vapor Levels in a Leaf	373
8.2F. Water Vapor Fluxes	375
8.2G. Control of Transpiration	376
8.3. CO ₂ Conductances and Resistances	378
8.3A. Resistance and Conductance Network	378
8.3B. Mesophyll Area	380
8.3C. Resistance Formulation for Cell Components	382
8.3D. Partition Coefficient for CO ₂	383
8.3E. Cell Wall Resistance	385
8.3F. Plasma Membrane Resistance	386
8.3G. Cytosol Resistance	387
8.3H. Mesophyll Resistance	387
8.3I. Chloroplast Resistance	388
8.4. CO ₂ Fluxes Accompanying Photosynthesis	389
8.4A. Photosynthesis	389
8.4B. Respiration and Photorespiration	391
8.4C. Comprehensive CO ₂ Resistance Network	395
8.4D. Compensation Points	396
8.4E. Fluxes of CO ₂	399
8.4F. CO ₂ Conductances	401
8.4G. Photosynthetic Rates	402
8.5. Water-Use Efficiency	404
8.5A. Values of WUE	404
8.5B. Elevational Effects on WUE	407
8.5C. Stomatal Control of WUE	407
8.5D. C ₃ versus C ₄ Plants	410
8.6. Problems	413
8.7. References	415

9. Plants and Fluxes

419

9.1. Gas Fluxes above Plant Canopy	420
9.1A. Wind Speed Profiles	421
9.1B. Flux Densities	422
9.1C. Eddy Diffusion Coefficients	423
9.1D. Resistance of Air above the Canopy	425
9.1E. Transpiration and Photosynthesis	425
9.1F. Values for Fluxes and Concentrations	426
9.1G. Condensation	428
9.2. Gas Fluxes within Plant Communities	429
9.2A. Eddy Diffusion Coefficient and Resistance	429

9.2B. Water Vapor	431
9.2C. Attenuation of the Photosynthetic Photon Flux	432
9.2D. Values of Foliar Absorption Coefficient	433
9.2E. Light Compensation Point	435
9.2F. CO ₂ Concentrations and Fluxes	435
9.2G. CO ₂ at Night	437
9.3. Water Movement in Soil	438
9.3A. Soil Water Potential	439
9.3B. Darcy's Law	441
9.3C. Soil Hydraulic Conductivity Coefficient	441
9.3D. Fluxes for Cylindrical Symmetry	443
9.3E. Fluxes for Spherical Symmetry	445
9.4. Water Movement in the Xylem and the Phloem	446
9.4A. Root Tissues	447
9.4B. Xylem	448
9.4C. Poiseuille's Law	448
9.4D. Applications of Poiseuille's Law	449
9.4E. Phloem	453
9.4F. Phloem Contents and Speed of Movement	454
9.4G. Mechanism of Phloem Flow	455
9.4H. Values for Components of the Phloem Water Potential	456
9.5. Soil–Plant–Atmosphere Continuum	459
9.5A. Values of Water Potential Components	459
9.5B. Resistances and Areas	461
9.5C. Specific Resistances and Conductances	465
9.5D. Capacitance and Time Constants	468
9.5E. Daily Changes	471
9.5F. Global Climate Change	473
9.6. Problems	476
9.7. References	479
Solutions to Problems	483
Appendix I. Numerical Values of Constants and Coefficients	529
Appendix II. Conversion Factors and Definitions	537
Appendix III. Mathematical Relations	541
III.A. Prefixes (for units of measure)	541
III.B. Areas and Volumes	541
III.C. Logarithms	541
III.D. Quadratic Equation	542
III.E. Trigonometric Functions	542
III.F. Differential Equations	543
Appendix IV. Gibbs Free Energy and Chemical Potential	545
IV.A. Entropy and Equilibrium	545
IV.B. Gibbs Free Energy	547
IV.C. Chemical Potential	549
IV.D. Pressure Dependence of μ_j	550
IV.E. Concentration Dependence of μ_j	553
Index	555